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Single leptoquark production associated with hard photon emission in *ep* collisions at high energies

V. Ilyin, A. Pukhov, V. Savrin, A. Semenov,
Institute of Nuclear Physics of Moscow State University, 119899 Moscow, Russia
and
W. von Schlippe
Queen Mary & Westfield College, London, England

Abstract

In this paper we consider single leptoquark resonance production associated with the emission of a hard photon. We have obtained analytical formulæ for differential and total cross sections for the cases of scalar and vector leptoquarks.

We have found that in reactions with scalar leptoquarks there is no photon radiation in some directions depending on the leptoquark electric charge (*the radiative amplitude zero – the RAZ* effect).

For vector leptoquarks the exact RAZ is present only in the case of Yang-Mills coupling. We propose to use the RAZ effect to determine the types of leptoquarks. We conclude also that this effect opens a possibility to measure the leptoquark anomalous magnetic moment.

1 Introduction.

During the last ten years many authors have considered the existence of leptoquarks as a possible extension of the Standard Model (SM) (see, for example, [1] and references therein). Such schemes are attractive because of the similarity of quarks and leptons with respect to the structure of electroweak interaction. Some fundamental problems of quantum field theory can be resolved with the help of such new bosons. A recent example is the attempt to explain the unification of the three gauge couplings at the grand unified theory scale [2] by introducing a scalar leptoquark isodoublet into the model. So it appears to be quite interesting to admit the possibility for the quark to convert into a lepton and back due to the emission of a new boson — the *leptoquark*. These hypothetical bosons are colour particles with lepton and baryon numbers. In this paper we refer to the leptoquarks as LQ.

Various general restrictions on possible sets of these new particles and their properties follow from low-energy experiments (proton stability, rare decays, quark-lepton universality etc.), see [3, 4, 5]. Among them are (i) baryon and lepton number conservation; (ii) chirality of fermion-LQ couplings ; (iii) some "fermion family" restrictions.

The principal mode of LQ production at electron-proton colliders is electron-quark fusion which gives rise to resonance peaks in the cross-section of ep collisions. The experimental investigations of such collisions at high energies allow one to measure LQ masses directly through the resonance peak position and to establish bounds in the (LQ mass, fermion-LQ coupling (λ)) plane. Direct searches for new particles by their s-channel resonances in the H1 and ZEUS experiments at HERA have been presented in Ref. [6]. The characteristic bounds for the LQ masses at $\lambda = 0.3$ lie in the interval 140 to 235 GeV depending on the LQ type. These bounds were derived from the analyses of data samples of $\approx 425\,\mathrm{nb}^{-1}$ accumulated by each of the two HERA experiments. With larger accumulated luminosity the whole kinematical range, up to 296 GeV, will be probed for the existence of LQ resonances. The next step in ep-collision experiments could be the LEP+LHC project with $\sqrt{s} = 1740\,\mathrm{GeV}$ and an annual luminosity about 1 fb^{-1}.

However a new important problem will arise after the observation of the LQ signal, namely the problem of identifying the leptoquark: it will be necessary to measure not only the LQ masses but also the fermion-LQ couplings and quantum numbers, such as electric charge, hypercharge etc.

In this paper we show a possibility to carry out the LQ identification using data from ep experiments. For this purpose we propose to investigate single LQ production associated with the emission of a hard photon. We have found that in this reaction there is no photon radiation in some directions depending on the LQ type. Following Ref. [7] we will call this effect *radiative amplitude zero (RAZ)*. The value of the RAZ angle depends essentially on the LQ electric charge. As a result the RAZ test gives us a possibility to determine the LQ type.

From a phenomenological point of view it is reasonable to consider the most general Lagrangian for fermion-LQ vertices satisfying the general restrictions listed above, with dimensionless couplings, and satisfying $SU(3)_c \times SU(2)_L \times U(1)_R$ gauge invariance. In this case a general phenomenological analysis can be made without reference to any concrete model. Such a Lagrangian was proposed in Ref. [4] for the first generation of fermions.

The interaction of scalar LQ with electromagnetic field can be described by a Lagrangian which is fixed by its electric charge:

$$\mathcal{L}^S_\gamma = (D^\mu \Phi)^+ (D_\mu \Phi) - M^2 \Phi^+ \Phi.$$

Here $D_\mu = \partial_\mu - ieQA_\mu$, A_μ is the electromagnetic field, and we denote a scalar LQ by Φ.

The Lagrangian for vector LQ interaction with electromagnetic field can be written in the following form:

$$\begin{aligned} \mathcal{L}^V_\gamma = ieQ[A_\mu \Phi^{+\mu\nu}\Phi_\nu &- A_\mu \Phi^+_\nu \Phi^{\mu\nu} + (1-\kappa) A_{\mu\nu} \Phi^{+\nu}\Phi^\mu] \\ &- (eQ)^2 [A^2(\Phi^+_\mu \Phi^\mu) - (A^\mu \Phi^+_\mu)(A^\nu \Phi_\nu)]. \end{aligned} \tag{1}$$

Here $\Phi_{\mu\nu} = \partial_\nu \Phi_\mu - \partial_\mu \Phi_\nu$, $A_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$, and the vector LQ is denoted by Φ_μ.

The LQ quantum numbers are collected in Table 1 and correspond to Ref. [4]. Here the third components of isospin are denoted by T_3 and the LQ electric charges by Q. In the following text we use notation, like S_3^{-1}, corresponding to $(LQ)^{T_3}_{2T+1}$, where T is the $SU(2)$ isospin.

Since one of the general low-energy restrictions is the chirality of the fermion-LQ coupling, we consider in our calculations only either left-handed couplings or right-handed ones using the same notation λ in both cases.

In Lagrangian (1) there is a free dimensionless parameter κ, the *anomalous magnetic moment* of the LQ. The value $\kappa = 0$ corresponds to the Yang-Mills structure and $\kappa = 1$ corresponds to *minimal coupling*.

We have carried out our analytical calculations using the CompHEP package [8].

2 Single leptoquark production

To study the LQ interaction with electromagnetic field we propose the following inclusive reaction:

$$e^{\pm} + p \to \gamma + LQ + X \tag{2}$$

with a hard photon in the final state.

An obvious starting point for the analysis of reaction (2) is the assumption that a sharp peak is observed in the reaction

$$e^{\pm} + p \to \ell + q + X. \tag{3}$$

This peak is a signal of the LQ resonant electron (positron) - quark fusion

$$e^{\pm} + q \to LQ. \tag{4}$$

In such a situation the mass of the new particle can be determined directly from the position of the sharp peak in the x distribution of the struck quark [4].

However in the literature there is no detailed investigation of a problem of determining other quantum numbers of the observed LQ. In this paper we propose a solution of this problem based on data from ep-collisions. Certainly, data from the collisions of other types can give necessary information (see, for example, [9] and references therein).

First, we note that one can determine the lepton chirality of the observed LQ by using polarized electron (positron) beams.

The spin of the new particle can be easily determined from reaction (3): for scalar LQ the distribution in the decay polar angle θ^* is isotropic in the LQ rest frame, whereas for vector LQ it has a characteristic $(1 + \cos\theta^*)^2$ dependence.

However it will be practically impossible to determine which flavour of quark or antiquark has produced this leptoquark. Indeed, the total resonance production cross section (4) is given by (cf. Ref. [4])

$$\sigma_{tot}(e^{\pm}p \to LQ + X) = \frac{\pi}{4s} \cdot \lambda^2 \cdot f_q(\frac{M^2}{s}) \cdot (J+1),$$

where J is the LQ spin ($J = 0,\, 1$), and $f_q(x)$ is the quark (antiquark) distribution function. We see that the value of the total cross section allows one to measure the product $\lambda^2 f_q(x)$ rather than the parton structure function at $x = M^2/s$ and λ separately. So in this way we cannot conclude what proton constituent was involved in the LQ production.

Furthermore, one could think of measuring the coupling constant λ directly from the shape of the observed resonance peak using the formulæ for the partial widths [4] in the scalar and vector cases correspondingly:

$$\Gamma^S_{LQ} = \frac{\lambda^2}{16\pi} \cdot M, \qquad \Gamma^V_{LQ} = \frac{\lambda^2}{24\pi} \cdot M.$$

Unfortunately, even for the electroweak value of the coupling constant, $\lambda \sim 0.3$, the partial width is too small, $\sim 0.002M$, to be resolved experimentally.

Another possibility to consider is the direct measurement of quark-jet charges event-by-event to assist in the identification of the LQ type. However, whereas existing methods work reasonably well for heavy quarks, they do require very large statistics in the case of light quarks (see, for example, [10]). Also, the known methods appear to work only for integrated characteristics, such as for instance asymmetry and partial widths.

We conclude that the analysis of resonant LQ production in *ep* collisions cannot help us in identifying the type of the observed new particle and, as a consequence, in measuring the fermion-LQ coupling constant λ. In the following we show the potential of reaction (2) in the identification of the observed new particle. We will show that it is essential to exploit the RAZ effect for this purpose.

3 Parton cross sections. Analytical results

In reaction (2) there are the following contributing exclusive subprocesses

$$e^{\pm} + q \to \gamma + LQ, \tag{5}$$

where q is a constituent quark of the proton. We consider the case when the LQ interacts only with fermions of the first generation, i.e. $q = (u, \bar{u}, d, \bar{d})$.

The amplitude for subprocess (5) is represented by three Feynman diagrams, see Fig. 1.

The contribution of a separate constituent quark in the integrated cross section of reaction (2) is expressed as the convolution of the subprocess cross section with the corresponding parton distribution function:

$$\sigma(s) \;=\; \int_{x_{min}}^{1} dx\; q(x,Q^2) \int_{-1}^{1} d\cos\vartheta_\gamma \cdot \frac{d\hat{\sigma}(\hat{s},\cos\vartheta_\gamma)}{d\cos\vartheta_\gamma} \cdot \Theta_{cuts}(E_\gamma,\vartheta_\gamma). \tag{6}$$

Here $\hat{\sigma}$ is the cross section of the corresponding subprocess (5), $\hat{s} = xs$, the quark distribution function is denoted by $q(x,Q^2)$ and the four-momentum transfer scale is taken to be $Q^2 = \hat{s}$. We denote the photon emission angle by ϑ_γ. The direction $\vartheta_\gamma = 0$ is along the proton beam. The function $\Theta_{cuts}(E_\gamma,\vartheta_\gamma)$ introduces the necessary kinematical cuts. The process under discussion is infra-red divergent, therefore we have to introduce the cut $E_\gamma > E_\gamma^0 > 0$.

We have calculated analytically the unpolarized squared matrix elements and cross sections for subprocesses (5). The electron and quark (u and d) masses are taken equal to zero in these calculations.

The squared amplitude for subprocesses (5) in the case of scalar leptoquarks can be written in the following form[1]:

$$|A|^2_S \;=\; \frac{e^2\lambda^2}{2} \cdot \frac{\xi^2+1}{(\xi-1)^2} \cdot \frac{(Q_e\upsilon - Q_q\tau)^2}{\upsilon\tau}. \tag{7}$$

Here q denotes the incoming quark or antiquark (u, d, $\bar{u}$, or $\bar{d}$), e is the elementary charge, Q_q and $Q_e = \mp 1$ are the quark, electron and positron charges respectively, in units of e. We also use normalized dimensionless Mandelstam variables

$$\xi \equiv \frac{\hat{s}}{M^2} \;=\; \frac{(p_e+p_q)^2}{M^2}, \qquad \tau \equiv \frac{t}{M^2} \;=\; \frac{(p_\gamma-p_e)^2}{M^2}, \qquad \upsilon \equiv \frac{u}{M^2} \;=\; \frac{(p_{LQ}-p_e)^2}{M^2}.$$

The total cross sections of the subprocesses (with scalar LQ) are given by

$$\hat{\sigma}^S(\xi,\delta_1,\delta_2) \;=\; \frac{\alpha\lambda^2}{8M^2} \cdot \frac{1}{\xi^2} \cdot \frac{\xi^2+1}{(\xi-1)^2} \cdot \left[L(\xi-1) - Q^2(\xi-1-\delta_1-\delta_2)\right].$$

Here $\alpha = e^2/(4\pi)$ is the fine structure constant and $Q = Q_e + Q_q$ is the LQ electric charge. In this formula (also in the corresponding formula for vector LQ)

$$L \;\equiv\; \log\frac{\xi-1-\delta_2}{\delta_1} + Q_q^2 \log\frac{\xi-1-\delta_1}{\delta_2}$$

and we have applied the cuts on the momentum transfer τ:

$$-\,\xi + 1 + \delta_2 \;<\; \tau \;<\; -\delta_1, \qquad \delta_{1,2} > 0, \tag{8}$$

The squared matrix element for vector LQ has the form[2]

$$|A|^2_V = \frac{e^2\lambda^2}{(\xi-1)^2} \cdot \left[(Q_q\tau - Q_e\upsilon)^2 K_0 \;+\; Q(Q_q\tau - Q_e\upsilon)K_1\kappa \;+\; Q^2 K_2 \kappa^2\right], \tag{9}$$

$$K_0 \equiv \frac{\xi^2+1-2\tau\upsilon}{\tau\upsilon}, \qquad K_1 \equiv \tau - \upsilon, \qquad K_2 \equiv \frac{\tau\upsilon}{2} \;+\; \frac{\xi}{8}\cdot(\tau^2+\upsilon^2).$$

The total cross sections of the subprocesses with vector LQ and with the cuts on momentum transfer (8) applied can be represented in the following form

[1] Results in the case of $S_3^{\pm 1}$ leptoquarks are greater by a factor of two.

[2] Results in the case of $U_3^{\pm 1}$ leptoquarks are greater by a factor of two.

$$\hat{\sigma}^V(\xi,\delta_1,\delta_2)=\frac{\alpha\lambda^2}{4M^2\xi^2(\xi-1)^2}\left\{(\xi^2+1)(\xi-1)L+\sum_{i=0}^{3}(A_i+B_i\kappa+C_i\kappa^2)\xi^i\right\}. \tag{10}$$

Here

$$A_0=2-2Q_eQ+\frac{5}{3}Q^2+\delta_1(Q^2+2)+\delta_2(Q^2+2Q_q^2)+2(\delta_1^2Q_e+\delta_2^2Q_q)Q+\frac{2}{3}(\delta_1^3+\delta_2^3)Q^2;$$

$$A_1=-3(Q_q^2+1)-4(\delta_1+\delta_2Q_q^2)-2(\delta_1^2Q_e+\delta_2^2Q_q)Q;$$

$$A_2=3(Q_q^2+1)+\delta_1(Q^2+2)+\delta_2(Q^2+2Q_q^2);\qquad A_3=-2+2Q_eQ-\frac{5}{3}Q^2;$$

$$B_0=-\frac{Q}{6}\left[Q+6(\delta_1Q_e+\delta_2Q_q)+3(\delta_1^2+\delta_2^2)Q+6(\delta_1^2Q_e+\delta_2^2Q_q)+4(\delta_1^3+\delta_2^3)Q\right];$$

$$B_1=\frac{Q}{2}\left[Q+4(\delta_1Q_e+\delta_2Q_q)+(\delta_1^2+\delta_2^2)Q+2(\delta_2^2Q_q+\delta_1^2Q_e)\right];$$

$$B_2=-\frac{Q}{2}\left[Q+2(\delta_1Q_e+\delta_2Q_q)\right];\qquad B_3=\frac{Q^2}{6};$$

$$C_0=-\frac{Q^2}{12}\left[1-3(\delta_1^2+\delta_2^2)-2(\delta_1^3+\delta_2^3)\right];$$

$$C_1=\frac{Q^2}{24}\left[4-3(\delta_1+\delta_2)-9(\delta_1^2+\delta_2^2)-2(\delta_1^3+\delta_2^3)\right];$$

$$C_2=\frac{Q^2}{8}\left[2(\delta_1+\delta_2)+\delta_1^2+\delta_2^2\right];\qquad C_3=-\frac{Q^2}{24}\left[4+3(\delta_1+\delta_2)\right];$$

Consider these formulæ in connection with the RAZ effect. The factor $(Q_e\upsilon-Q_q\tau)^2$ in Eqs. (7,9) gives the RAZ, i.e. the absence of photon emission in some direction. Note that for vector leptoquarks the exact RAZ is present only in the Yang-Mills case ($\kappa=0$) due to the κ^2 term.

The value of the corresponding polar angle is determined by the relation $Q_e\upsilon=Q_q\tau$. We have the formula for the RAZ angle in the CMS of the pair $(e^{\pm}_{in},\, q_{in})$

$$\cos\vartheta^*_{RAZ}=\frac{Q_e-Q_q}{Q}.$$

Due to different values of LQ charges the RAZ effect exists only for some of the leptoquark types collected in Table 2. As a result, we have a possibility to identify the type of the discovered leptoquark by studying the distribution in the photon emission angle.

In Fig. 2 we show the distributions in the photon emission angle in the CMS of the $(e^{\pm}_{in},\, q_{in})$ pair.

In the laboratory frame the RAZ angle is changed by the corresponding Lorentz boost. This boost depends on $\hat{s}=xs$, so the RAZ is shifted and smoothed due to the distribution in x. However this distribution has a rather sharp peak for a small enough cut over the photon energy. As a result, for the rough estimates we can use $\hat{s}=M^2$, and in order to estimate the RAZ angle in the laboratory frame we can use the following formulæ

$$\cos\vartheta_{RAZ}\;=\;\frac{\cos\vartheta^*_{RAZ}+\hat{\upsilon}}{1+\hat{\upsilon}\cdot\cos\vartheta^*_{RAZ}},\qquad \hat{\upsilon}\;=\;\frac{M^2-4\mathcal{E}_e^2}{M^2+4\mathcal{E}_e^2}.$$

Here the electron beam energy is denoted by $\mathcal{E}_e$.

Note that at HERA the RAZ is shifted significantly whereas at LEP+LHC the case of $M=200\,\mathrm{GeV}$ practically corresponds to the CMS. We give some RAZ angles for different LQ masses in Table 2.

A final remark is that cross sections with the RAZ effect in the case of vector LQ are sensitive to the value of the LQ anomalous magnetic moment, the exact RAZ being present only for the Yang-Mills type of photon-leptoquark coupling. This effect opens therefore a possibility to measure the LQ anomalous magnetic moment.

Conclusions

In this paper we have analysed the formulas obtained with the help of the CompHEP package for the process of single leptoquark production associated with hard photon emission which reveal the absence of radiation at some photon emission angles. We propose to use this so-called radiative amplitude zero (RAZ) effect as a tool for identifying the leptoquarks that could manifest themselves as resonance peaks in *ep* collisions. We have shown that for vector leptoquarks the exact RAZ effect is present only for the Yang-Mills couplings. This opens a possibility to probe the leptoquark anomalous magnetic moment.

Here we have concentrated on the analytical results for subprocesses with two particles in the final state. However preliminary numerical calculations show that the same conclusions can be drawn for the more realistic case taking into account parton distributions and three body final states. The results of accurate numerical calculations will be presented in future publications.

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Tables

LQ name	*Lepton chirality*	*Spin*	*F*	$SU(3)_c$	$Y=2(Q-T_3)$	T_3	Q
S_1	L,R	0	2	3	$-\frac{2}{3}$	0	$-\frac{1}{3}$
$\tilde{S}_1$	R	0	2	3	$-\frac{8}{3}$	0	$-\frac{4}{3}$
						-1	$-\frac{4}{3}$
S_3	L	0	2	3	$-\frac{2}{3}$	0	$-\frac{1}{3}$
						1	$\frac{2}{3}$
R_2	L,R	0	0	$\bar{3}$	$-\frac{7}{3}$	$-\frac{1}{2}$	$-\frac{5}{3}$
						$\frac{1}{2}$	$-\frac{2}{3}$
$\tilde{R}_2$	L	0	0	$\bar{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{2}{3}$
						$\frac{1}{2}$	$\frac{1}{3}$
U_1	L,R	1	0	$\bar{3}$	$-\frac{4}{3}$	0	$-\frac{2}{3}$
$\tilde{U}_1$	R	1	0	$\bar{3}$	$-\frac{10}{3}$	0	$-\frac{5}{3}$
						-1	$-\frac{5}{3}$
U_3	L	1	0	$\bar{3}$	$-\frac{4}{3}$	0	$-\frac{2}{3}$
						1	$\frac{1}{3}$
V_2	L,R	1	2	3	$-\frac{5}{3}$	$-\frac{1}{2}$	$-\frac{4}{3}$
						$\frac{1}{2}$	$-\frac{1}{3}$
$\tilde{V}_2$	L	1	2	3	$\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
						$\frac{1}{2}$	$\frac{2}{3}$

Table 1: Leptoquark quantum numbers.

	M $[GeV]$	ϑ_{RAZ} $[deg]$	
		$\vartheta^*_{RAZ} = 60^\circ$	$\vartheta^*_{RAZ} = 78.5^\circ$
		S_3^{-1}, $V_2^{-\frac{1}{2}}$ (L) $\tilde{S}_1$, $V_2^{-\frac{1}{2}}$ (R)	$R_2^{-\frac{1}{2}}$, U_3^{-1} (L) $R_2^{-\frac{1}{2}}$, $\tilde{U}_1$ (R)
HERA	150	26	36
	200	20	27
	250	16	22
LEP+LHC	200	60	78.5
	300	42	57
	500	26	36
	1000	13	18
	1500	9	13

Table 2: RAZ angles in dependence on LQ mass.

Figures

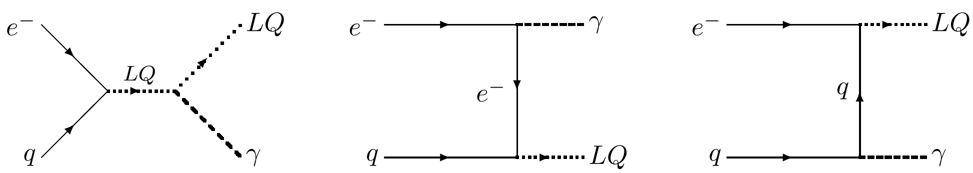

Figure 1: Feynman diagrams for subprocesses $e^- + q \to \gamma + LQ$

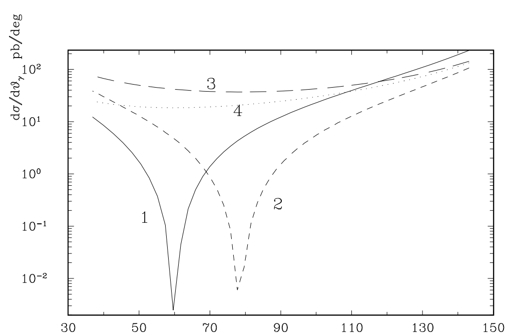

Figure 2: Angular distributions in the CMS for scalar LQ at $M_{LQ} = 300\,\mathrm{GeV}$, $\hat{s} = (304\,\mathrm{GeV})^2$ and $\lambda = 0.3$. 1) $e^- + d \to \gamma + S_3^{-1}$; 2) $e^+ + u \to \gamma + R_2$; 3) $e^- + u \to \gamma + S_1(S_3^0)$; 4) $e^+ + d \to \gamma + \tilde{R}_2$